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Abstract Industrial ecology is both a vision, a research field, and a source of inspiration for practical work. Its proponents aim to contribute to sustainable development by closing materials cycles and realising a fundamental paradigm shift in the thinking concerning industry–ecology relations. Dominant research lines in industrial ecology focus on industrial metabolism and life cycle tools. The underlying assumption is that the flow and transformation of materials can be managed through the correcting of market and regulatory failures which are causes of environmental degradation. This literature review suggests, on the one hand, that the manageability of the flow of materials is currently limited by market and regulatory failures which inhibit the implementation of the principles of industrial ecology and, on the other hand, that the flow and transformation of materials are only partly affected by prices, information and laws.

Key words Industrial ecology · Review · Governance of material flows · Dematerialisation

Introduction

The words 'industry' and 'ecology' were combined in the phrasing of 'industrial ecology' in the late 1980s, when two notions gained a solid foothold in the minds and perspectives of those working for sustainable development. One notion was that the minimisation of waste and emissions in individual process steps or products may not necessarily result in an overall reduced environmental impact. The other was that in some instances money could be made by a clever reduction of waste, emissions or resource utilisation. These two notions gave birth to a variety of concepts that renewed the debate concerning the question of sustainable development. Whereas some of the new concepts focus on products (e.g. life-cycle assessment, design for the environment) or facilities and production processes (e.g. pollution prevention), industrial ecology focuses on industrial systems. In this paper, industrial ecology is discussed as a vision for a sustainable world, as an emerging interdisciplinary research field, and the author demonstrates how it can be made operational at different systems levels.

The vision

Industrial ecology finds its legitimation in the question of what the environmental impact would be if, within a period of several decades and with a growing world population, each individual person enjoys, ideally, a standard of living common to the Western industrialised countries during the 1990s. The amount of natural resources required to sustain the accompanying level of consumption would probably not be available on this planet and the levels of pollution and waste generated would probably exceed the world's regenerative capacity (Frosch and Gallopoulos 1989). Phrased differently, if at any time overall environmental impact is a function of three factors – the size of a population, the level of industrial and economic activity of that population, and the environmental impact of its industrial and economic activities – then the question is, by how many orders of magnitude would the environmental impact of these activities need to be reduced for the overall environmental impact to remain constant if the population increases considerably and its per capita income – a measure of industrial and economic activity – multiplies? Furthermore, what if the current environmental impact already exceeds the regenerative, or carrying, capacity of that environment? Further discussions of this IPAT (environmental impact as a function of population, affluence and technology) equation and the related 'factor X' debate are found in, e.g., Ehrlich and Holdren (1971), Stern et al. (1997), Allenby (1998b) and Reijnders (1998).
Such arguments have had a strong impact in generating widespread support for the view of approaching sustainability through increased eco-efficiency (Schmidheiny 1992) and breakthrough innovations in technology and consumption (Von Weizsäcker et al. 1997). Industrial ecology can be viewed as one perspective that helps to find "imaginative solutions to these resource and environ-

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mental problems", by adopting the notion that "the industrial system ought to be modified so as to mimic the natural ecosystem in its overall operation" (Frosch and Gallopoulos 1992:271). In this way, industrial ecology is the basis of a major transformation in industrial society; it is supposed to substitute the "free market framework" as the dominant social paradigm upon which society's institutions are built (Ehrenfeld 1997a).
The metaphor from biology, popularised by Frosch and Gallopoulos in 1989, is the most important conceptual contribution of industrial ecology, although the appropriateness of the metaphor has been challenged on various grounds (e.g. Boons and Baas 1997). Interestingly, microbiologists have used the metaphor of industrial manufacturing processes in an attempt to model metabolic pathways within the cell (Ortega et al. 1999); the industrial ecology metaphor is in reverse. In an industrial ecosystem "the consumption of energy and materials is optimised and effluents of one process...serve as the raw materials for another process" (Frosch and Gallopoulos 1989:94), much like nutrient flows in biological ecosystems. The industrial network is seen as a system of mutually dependent transformation processes which forms an interrelated part of a larger whole, "analogous in its functioning to a community of biological organisms and their environment" (Frosch and Gallopoulos 1992:272). As such, "industrial metabolism" (Ayres 1989) – the understanding of the flow of materials and energy both within and between industrial and ecological systems, as well as their transformation in products, by-products and effluents – is fundamental to industrial ecology (Garner and Keoleian 1995), because a better understanding of material flows is a first step to increasing the eco-efficiency of society's metabolism by closing material flows into loops of recycling and reuse.
This latitude in the concept of industrial ecology – analysing the flow of materials and energy at the systems level in a specific geographical entity – is an important extension to concepts such as product stewardship and integrated substance chain management; these concepts take the production and use of specific products 'from cradle to grave' into account. Because of the adoption of life-cycle thinking, industrial ecology and the latter two concepts extend earlier concepts such as end-of-pipe pollution control and pollution prevention. Both pollution prevention and industrial ecology aim to reduce emissions and waste, yet a further distinction between the two concepts is that pollution prevention is oriented toward single firms or facilities, stressing activities within the firm, whereas industrial ecology is oriented toward dependencies and shared activities across firms. In its geographical scope, industrial ecology may refer to the entire world (Socolow 1994), river basins such as the Rhine (Stigliani et al. 1993), the economy of a specific nation or region (Lowe 1993; Sagar and Frosch 1997), individual industries (Frosch and Gallopoulos 1989), or even companies (Tibbs 1992; Greadel and Allenby 1995; Van Berkel and Lafleur 1997; Esty and Porter 1998). 'Industrial' in this context is not narrowly understood as 'pertaining to manufacturing firms' but rather refers to the activities of *Homo economicus*, including the energy and materials transformations in households and through consumption (Lifset 1998).
Thus, industrial ecology aims to contribute to sustainable development through two operational objectives: closing materials cycles, and realising a fundamental paradigm shift in the thinking concerning industry–ecology relations (O'Rourke et al. 1996). The remainder of this paper focuses on research into the first operational objective. The following delineation of the various research lines is based on a content analysis of the articles published so far in the Journal of Industrial Ecology [JIE 1(1) and 2(3), 1997–1998] and in the 1997 special issue on industrial ecology of the Journal of Cleaner Production JCP 5(1–2)], complemented by other papers if relevant to the discussion. As dedicated outlets for refereed, scientific work on industrial ecology, the articles in these journals are considered representative of state-of-the-art thinking on industrial ecology in the late 1990s.

Research field

Industrial ecology constitutes an emerging, multidisciplinary research field, whose researchers share the broad vision sketched above. Researchers in the field would probably accept the following attributes of industrial ecology (Garner and Keoleian 1995):

1. A systems view of the interactions between industrial and ecological systems.
2. The study of material and energy flows and their transformations into products, by-products and waste materials through industrial and natural systems (industrial metabolism).
3. A multidisciplinary approach.
4. An orientation toward the future.
5. A change from open, linear processes to closed, cyclical processes so that the waste from one sector is used as an input for another.
6. An effort to reduce the environmental impact of industrial systems on ecological systems.
7. An emphasis on the harmonious integration of industrial activity into ecological systems.
8. The idea of making industrial systems emulate the more efficient and sustainable natural systems.
9. The identification and comparison of industrial and natural systems hierarchies, which indicate areas of potential study and action.

However, there is not (yet) a clear demarcation of the field. Some restrict industrial ecology to the study of biological, chemical and physical processes (Garner and Keoleian 1995), whereas others include the study of informational, legal and economic incentives in industrial ecology (Frosch 1995; Sagar and Frosch 1997), or even the study of inter- and intra-organisational structures, arrangements and coordination (Dillon 1994; Boons and Baas 1997; Schwarz and Steininger 1997) and consumption (Stern et al. 1997). Despite a shared unit of analysis – the flow and transformation of materials and energy – different research approaches to industrial ecology can be distinguished. The first aims at describing material and energy flows, the second at their control through traditional governance instruments such as hierarchy, the market and the law. To be effective, this approach requires environmentally relevant information to be collected and processed for use in decision making. Various tools are being developed to that end. Finally, observing that the control of material and energy flows through traditional governance instruments is not the entire story, new governance instruments are being developed.

Description of flows and transformations

Descriptive research in industrial ecology focuses on questions such as: what do material and energy flows and their transformations look like? and what is their impact on the natural environment? In terms of system boundaries, the objects of study may be geographical entities as defined by administrative or economic boundaries, or by the flows and transformations of elements, materials, or products. They make use of the underlying material-balancing principles of industrial metabolism (Ayres 1989). For example, the industrial metabolisms of elements such as chlorine (Ayres 1997, 1998a; Ayres and Ayres 1997; Kleijn et al. 1997; Tukker et al. 1997a) and lead (Socolow and Thomas 1997), of materials such as paper [JIE 1(3), special issue] and polyvinyl chloride (PVC) (Tukker et al. 1997b), and of products such as chlorofluorocarbons (CFC) (Papasavva and Moomaw 1997) have been analysed extensively.

Industrial metabolism provides a useful understanding of the interrelationship of society with nature (Fischer-Kowalski 1998). There is conceptual clarity, but theoretical and operational specifications are not yet properly and consistently settled (Fischer-Kowalski and Hüttler 1999). In this respect, current studies of industrial metabolism have the dual interest of fact finding and development of methodology. According to this background, several issues for future research need to be pointed out. First, the choice of elements, materials and products is biased towards those that are released as non-fugitive, non-dilute, point-source industrial wastes or used as non-dissipative consumer products (O'Rourke et al. 1996; Rejeski 1997). There is little consideration of how dissipative products such as detergents, coatings, fuels, food, fertilisers and pesticides would fit into an industrial ecology. To some extent, green chemistry (Anastas and Breen 1997) may help reduce the environmental impact of dissipative products, but it leaves unquestioned the open-ended character of these flows. Second, the metabolism of elements, materials and products within industry requires the input of energy, as does the closing of currently open-ended flows by recycling. However, the energy component in both the current, open-ended and the future closed flows remains largely unresearched (Andrews et al. 1994; O'Rourke et al. 1996). Finally, in some articles, systems boundaries have implicitly been defined; in most they are defined in terms of administrative boundaries (country, region). This choice of systems boundaries probably reflects the interests of the data-collecting bodies, which are often national or supranational public bodies or industry associations. Rejeski (1997) considers cross-border material flows as one of the challenges to industrial metabolism. From the industrial ecology perspective it would, however, be more relevant to look for boundaries as defined by the area within which an element, material or product is transformed and transported by economic, physical, chemical and biological forces. To choose natural boundaries, such as river basins, as systems boundaries does not resolve the problem since the economically motivated flow of materials and energy tends not to be restricted by oceans, watersheds and mountain ridges.

Governance of material flows: traditional approaches

Industrial ecology aims to deliberately and rationally influence material and energy flows (Ayres 1998b). Many studies share the neoclassical economic assumptions that decision makers, whether product developers, corporate executives, public administrators or consumers, would make different decisions if they had the information to allow them to evaluate the broader environmental consequences of their decisions, if they had to pay prices reflecting the monetary value of the externalities of the use of materials and energy, or if they were not told to do otherwise by regulators. The analysis is that, fundamentally, environmental problems are caused by market and regulatory failures that can be corrected if decision makers were given the 'right' information and were exposed to the 'right' prices (O'Rourke et al. 1996).

The collection and sharing of information on environmentally relevant aspects of production and consumption are critical components of industrial ecology. Industrial ecology requires firms to cooperate more closely in order to realise its promise of increased environmental benefits. Therefore, firms need to collect, process and share data on resource utilisation, waste-stream monitoring, and intra- and interfirm component flows. In this respect, information systems can be very helpful (Shaft et al. 1997). Consequently, many corporate functions now have to deal with environmental issues, whereas before they did not; this needs careful planning, top-management commitment and dedicated programs to involve those functions (Dillon 1994).

Consumers, too, need to know about the environmental impact of products and services if they are to value reduced environmental impact in their purchases. Third-party voluntary environmental product labels were introduced as a means of informing consumers accurately about the environmental qualities of products. According to Salzman (1997), such labels have proven not to be very effective in influencing consumers' buying behaviour, but they may have resulted in reduced environmental impact in different ways, e.g. by stimulating competition among producers for the label and by enabling public and institutional purchasing programs to select labelled products over non-labelled products.

Not only the information but also the prices need to be right. Various studies deal with the questions of whether and how recycling can be economically viable and environmentally beneficial. Some of the lessons learnt include the apparent difficulty of integrating environmental data meaningfully into economic modelling (Van Beukering and Duraiappah 1998) and the vulnerability of recycling systems to changing costs of collection, transportation and final disposal of unprocessable wastes (Isaacs and Gupta 1997; Lave et al. 1998). However, it is suggested by Lave et al. (1998) that recycling schemes can be made more robust if clever solutions are found for collecting goods to be recycled, if those goods have been designed in order to meet critical specifications of the recycling system and if the goods are recycled into something that is marketable. Porter's competitive strategy framework can be a helpful tool for such solutions. First, the value chain (Porter 1985) can be used to assess where high cost limits the overall efficiency of the recycling system. Second, the five forces framework (Porter 1980) can be used to assess whether and where stable niches for the application of recovered material exist and whether regulation is required to enhance the stability of that niche (that is, provided the lack of recycling is considered a market failure and that regulation to repair this failure is considered socially desirable).

Esty and Porter (1998) claim that adopting the industrial ecology perspective may enhance a firm's competitive position through increasing resource efficiency at three levels: within the firm's value chain, within the value system it shares with its suppliers and distribution channels, and beyond the value system in a situation of industrial symbiosis. The waste exchange network in Kalundborg, Denmark, (to be discussed later) is one example of industrial symbiosis; the one that developed in the Austrian province of Stryria is another.

Schwarz and Steininger (1997) studied why companies participate in the Styrian network. They found that cost calculations constitute the main reason, both for companies offering wastes as raw materials (increased revenues, reduction of disposal costs) and for companies procuring these wastes (cost reductions). More interesting is the question of how the exchanges within the network are governed. Most of the participating companies have entered into long-term contractual agreements or even joint-ownership subsidiaries (quasi-vertical integration; Harrigan 1984). Alternative governance structures, such as integrating waste valorising activities within the company, or trading waste through spot market arrangements, are considered less efficient (Schwarz and Steininger 1997), essentially because of higher transaction costs to both the vendor and the seller (Williamson 1985). Transaction costs would be high in a spot market for the trading of waste because of uncertainty regarding the availability in terms of quantity and quality of the wastes to be traded. The need for continuity in the business processes by the vendor and the seller makes it too costly for either of them to depend on the spot market. The integration of waste valorising activities arguably involves a costly diversification of business activities, including investment in specialised assets, for which the firm has neither the financial capability nor the required competence.

To some extent, the success of the Kalundborg and Styrian industrial symbioses depends on the creativity of the participating firms' managers and engineers to find profitable options for the handling of what otherwise would have been waste materials. It equally depends on the existence of a basic level of trust among the managers and engineers of the participating firms. In the absence of trust, long-term contractual agreements could not have been established to overcome spot market failure. These two conditions need not prevail. There may, consequently, exist situations in which taking the industrial ecology perspective does not result in enhanced firm competitiveness, e.g. if the associated cost exceeds the benefits, or if following the suggestions of industrial ecology would lead to undertaking activities that are not valued or permitted in the prevailing economic and institutional frameworks (Esty and Porter 1998).

A clear example of the latter is shown in the study by Heaton and Banks (1997). The study details how the US statutory system of environmental regulation inhibits technological innovation. Firms are required to conform with different administrative regimes for air, water, waste, etc. 'Perverse' incentives are in place that stimulate firms to use older, more polluting equipment because newer technologies need to meet stricter pollution control levels and hence are more expensive. Moreover, they argue that a regulatory system based on 'best available technology' standards (such as in the US) impedes innovation, because the rate of technological innovation tends to be quicker than the rate at which regulators adapt their definition of what is the 'best' available technology (Heaton and Banks 1997). In such situations, legislative reform is required in order for companies to adopt environmentally more beneficial technologies and practices.

The suggestion from this section would be that, indeed, the market can be an important governance mechanism for improving the management of material flows, but not unconditionally. To put the proper incentives (information, prices) in place is troublesome, and if in place they may operate in unexpected ways. Moreover, recycling markets tend to be vulnerable and take time to develop.

Tools

Additionally, many articles have been published on the development and application of practical tools for industrial ecology, such as material flow analysis (MFA), life-cycle assessment (LCA) and design for environment (DFE). Such tools are useful in getting the information and prices right. They are essential, although probably not sufficient, contributions to further industrial ecology. Table 1 lists the various articles discussing aspects of these tools. Each of these tools has its own body of literature, journals and practitioners, which severely limits an exhaustive discussion. Table 1 gives a short characterisation of the relationships between the various tools.

Material flow analysis (MFA) and substance flow analysis (SFA) are basic analytical tools for industrial ecology derived from the first law of thermodynamics: what goes in must come out because matter cannot get lost. The life-cycle assessment (LCA) of products extends to these analyses by attempting to quantify the environmental impact of the use of materials and substances in particular product designs. The resulting environmental profile of a product can be used for comparison with competing products or for suggesting ways to improve that particular product design, i.e. design for environment (DFE). The LCA methodology can also be used to justify the eco-labelling of product designs. When applied to production processes, MFA/SFA is helpful in identifying inefficiencies or leaks, which in turn can be remedied by process innovations, i.e. cleaner production or pollution prevention (PP, P2). In order to determine whether or not any progress has been made one needs environmental performance measures that heavily rely on process data. Both managerial and environmental information systems are likely to contain relevant data. These are the most important tools of the 'industrial ecology toolbox', each of which has one or more of four basic functions (Van Berkel et al. 1997a):

1. To enable the identification, quantification and allocation of environmental interventions to (parts of) production processes and product life cycles.
2. To facilitate the generation of improvement options for product designs, product life cycles and production processes.
3. To provide a structured approach for the evaluation of, and priority setting among, environmental interventions and/or environmental improvement options.
4. To specify procedures and routines for the development of industrial ecology projects.

For example, several steps need to be distinguished in the LCA methodology, including the identification, classification and evaluation of the environmental interventions. Likewise, pollution prevention is often presented as a procedure in which the environmental interventions of a facility are first identified, then options for improvement are generated and prioritised, often cost efficiency is the decision criterion, and finally the most efficient options are implemented.

An obvious problem with information-based tools such as MFA, LCA and DFE is that they require enormous amounts of data which are costly to collect, while it remains doubtful whether information would in itself be helpful given the trade-offs, ambiguities, uncertainties and complexities in product development, specially if the product is more complicated than, e.g., a Styrofoam cup (Hocking 1991). Moreover, it appears that the environmental impact of products is determined to a greater extent by the question of how consumers use a product than by the product design itself (Udo de Haes 1997). Finally, it has been argued that to focus on the environmental benefits of one design alternative over another may entirely miss the more fundamental question of whether the functionality or service of that product cannot be delivered by different means (O'Rourke et al. 1996).

Governance of material flows: new approaches

Several authors are less convinced of whether material and energy flows can actually be managed through information, regulation and prices. For example, Harrison (1998) points out that collaborative approaches to environmental protection, such as negotiated agreements, flexible enforcement, voluntary codes and agreements, have been

Table 1
Development and appraisal of tools for industrial ecology. *LCA* Life-cycle assessment; *IE* industrial ecology; *EMAS* eco-management and auditing scheme, as developed by the EC

Materials flow analysis	Intellectual history of materials flow analysis	Fischer-Kowalski (1998)
Life-cycle assessment	Limits of life-cycle assessment	Owens (1997)
	Importance	Ehrenfeld (1997b)
	Objectives	Greadel (1997a)
	Service industry	Greadel (1997b)
	Spatial differentiation	Potting et al. (1998)
Design for environment	Phasing of design for environment	Hoffman (1997)
	Use of LCA in design for environment	Sheng and Worhach (1997)
	Data logs for component reuse	Klausner et al. (1998)
Cleaner production and pollution prevention	Relation with IE	Oldenburg and Geiser (1997); Van Berkel et al. (1997b)
Environmental performance measures	Ranking potential environmental impacts	Wright et al. (1997)
Information systems	EMAS as information systems	Liedtke et al. (1998)
		Shaft et al. (1997)

devised because of the difficulty of implementing traditional 'command and control' regulation and market-based incentives. Little is known, however, about their efficacy and efficiency. It might be the case that rigorous evaluation of such cooperative approaches reveals as much about the specific policy instrument design as about companies' motives and abilities to join them.

External conditions and internal motivations other than information, regulation and prices may also play a role in the opportunity or incentive for companies to initiate industrial ecology activities. For some companies in some industries, external forces such as globalisation of trade and competition, and flexible specialisation, shape their scope for strategic decision-making on use of materials (Boons and Baas 1997; Bragt et al. 1998). Such forces may prove considerable barriers for these companies to participate in local industrial ecology initiatives, especially if these companies are based in small countries and depend for the larger share of their turnovers on foreign sales. However, for other companies in other industries, such as construction, patterns of use of materials, changes in the use of materials, and the diffusion of those changes to other companies and throughout their industrial sectors, are severely restricted not only by their institutional environment (Lundvall 1992; Nelson 1993), but also by local climatic and geological conditions (Goverse 1999). Yet other companies may deliberately follow industrial ecology strategies without the prevailing regulatory or market incentives commanding them to do so. One example is an outdoor apparel manufacturer that decided to substitute organically for conventionally grown cotton in its garments (Chouinard and Brown 1997). Prices and information were significant barriers to overcome, but of greater importance was a paradigm shift in this company's management team, which made them accept the risk of a far less competitive cost structure. Because of the paradigm shift, the company was motivated to help existing suppliers adopt and to look for new suppliers meeting new quality standards (Chouinard and Brown 1997).

At a more fundamental level, the traditional governance approaches to, and tools of, industrial ecology can be criticised on the underlying assumptions of how firms make decisions (O'Rourke et al. 1996; Taylor 1996). Industrial ecology tends to view material and energy flows, as well as their transformations, as the combined result of natural forces and the aggregate productive and consumptive activities of numerous firms and consumers, whose decisions are primarily guided by direct economic and legal constraints. Within this perspective, Rejeski (1997) points out that too little attention has been given to the service sector and household consumption as mobilisers of material flows. Beyond this perspective, industrial ecology has hardly begun to consider strategic decision-making, interfirm collusion, the exercise of power, mimetic behaviour, cultural preferences, socio-economic institutions, etc., both as additional explanatory factors for the understanding of why material and energy flows have materialised as they have, and, in some instances, as reasons for the difficulty of changing those material and energy flows. In this context, Jackson and Clift (1998) argue that industrial ecology needs a "theory of agency". Additionally, research into the relationships between technologies, industries and socio-economic institutions is difficult to find in the context of industrial ecology, despite claims of its system's perspective. Systems of production and consumption are not invented but tend to develop in a complex way, in which coincidences and unanticipated (at times undesired) consequences intertwine with the actions that follow upon the good (or bad) intentions of individuals, organisations and institutions (Ruth 1998).

If industrial ecology – in its most radical interpretation – is about a fundamental transformation of the modern, Western industrialised society, then the understanding of how, and in what direction, that society develops is crucial, including an understanding of what globalisation actually is, what its environmental impact is, and what the mechanisms driving its development are (Bragt et al. 1998). Similar question hold for the development of a 'service economy' in which various types of services (Greadel 1997b) with different material implications substitute for traditional products. Whether the patterns of interaction and transaction between companies and consumers change would be more fundamental than, and underlie, a change in technology.

Putting theory into practice

Rejeski (1997) argues that industrial ecology should also be applied science. Industrial ecologists should make their point clear in the arena of public policy making. Eco-industrialists should face the consequences of their prescriptions in order to make clear whether and how their views complement, improve or contradict current wisdom. The practical value of industrial ecology is being explored in two directions (Erkman 1997). One direction is the local application of the principles of industrial ecology in the development of eco-industrial parks. The other is the exploration of reduced resource intensity of production and consumption at the societal level through dematerialisation – which is understood to include product-life extension (Stahel 1994), decarbonisation and the substitution of services for products.

Eco-industrial parks

An eco-industrial park (EIP) is: "A community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resources issues...By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realise if it optimised its individual performance only. The goal of an EIP is to improve the economic performance of the participating companies while minimising their environmental impact" (Lowe 1997:58). The paradigmatic exemplar of an eco-industrial park is the 'industrial symbiosis' between a number of companies in and around the town of Kalundborg (Denmark) that developed over a period of 25 years through bilateral expansions (Garner and Keoleian 1995; Ehrenfeld and Gertler 1997; Grann 1997). The Kalundborg eco-industrial park is based on the exchange of wastes and heat between a coal-fired power plant, an oil refinery, a pharmaceutical plant and a plasterboard manufacturing plant (Fig. 1). It has not been the result of a careful planning process, but rather of a gradual development of cooperation between industries and the municipality of Kalundborg since the early 1960s, when the initial ideas were being discussed in the local social club (Ehrenfeld and Gertler 1997). Although the Kalundborg example is the most well known, other conceptual models for eco-industrial parks can be found, including the development of eco-industrial parks either at greenfield sites or through the renewal and restructuring of existing industrial parks (Chertow 1998).

During the 1990s, the concept of the eco-industrial park has quickly developed into a planning tool for industrial development in both industrialized and developing countries. Although the Kalundborg example indicates that self-organisation is an important factor in the development of industrial ecosystems, several examples exist where university researchers, specialised consultants, and personnel from economic and environmental development agencies have contributed to developing eco-industrial parks in both industrialised and developing countries (Lowe 1997). Several conditions for success have been mentioned: a clear vision of the park's values and performance objectives, careful screening of new companies, methods and information to support companies in seeking by-product trades, flexibility in recruitment strategy, and assurance of continuing support. Challenges and risks that need to be faced include undesired resource dependencies, technological lock-in, leaking of proprietary information, and uneven quality (Lowe 1997), which are essentially the same principal-agency problems stemming from risk of misuse of private information that pertain in any collaborative venture.

Dematerialisation

Dematerialisation refers to the absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output (Cleveland and Ruth 1998). It is considered a crucial strategy for advancing industrial ecology at the societal level (e.g. Herman et al. 1989; Von Weizsäcker 1998). The suggestion to develop a service economy that is based on the delivery of function rather than products intermingles with other debates on dematerialisation. For several decades, dematerialisation has been a central issue in concerns over society's dependency of, and impact on, natural resources. Society's intensity of materials use has strategic, geo-political, and national security implications, in addition to environmental significance (Allenby 1998a). Some basic level of materials autarchy is striven for, especially in the US, which may be realised by increasing direct control over, or reducing the level of dependency on, critical resources.

There is a lively debate on the topic of dematerialisation. The relevance of this debate for industrial ecology is twofold. First, if it were the case that economies at a certain point in their development do dematerialise, then the need for a radical change in society's metabolism – as advanced by industrial ecology – would be less pressing. Second, the research methods developed for empirical research into the dematerialisation thesis can also be used

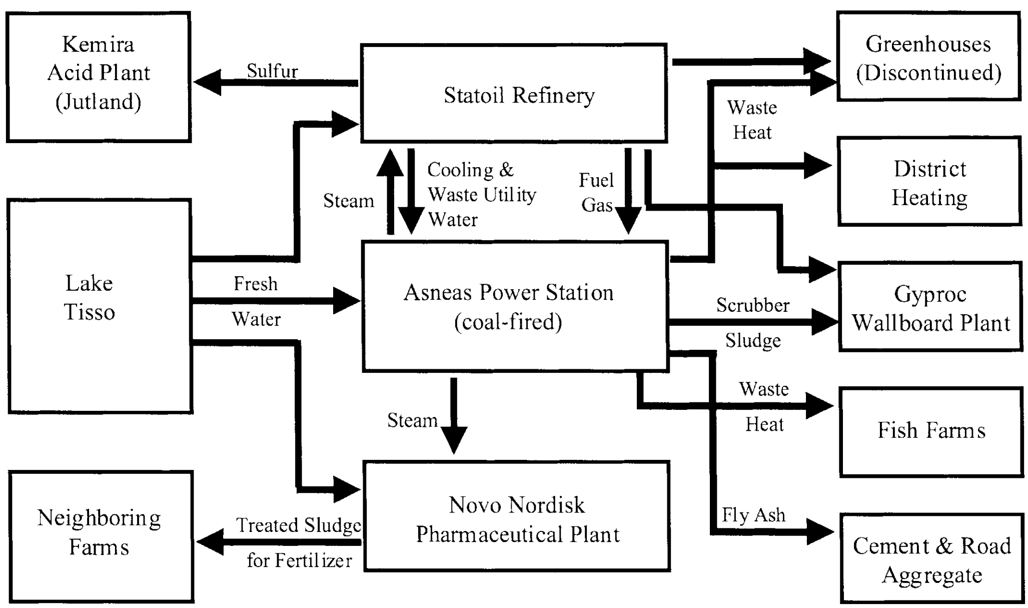

Fig. 1
Kalundborg eco-industrial park

to evaluate to what extent industrial ecology's efforts to make society less material-intensive are effective. The following presents several positions taken and an evaluation of the current state of knowledge.
Malenbaum (1978) sees dematerialisation as a consequence of changing demand for end products in different stages of economic development, e.g. because of increased demand for services and for products with higher added value, resulting in per capita reduction of materials intensity. So do Larson et al. (1986), who claim that when the market for a particular basic material is saturated, its use rate as measured in kilograms per unit of gross domestic product declines and that at a later stage even its per capita consumption may start to decline. Sources of per capita dematerialisation may originate from process or product innovations, i.e. a more efficient use of materials, from materials substitution and from changing consumer preferences due to higher income levels. The additional pound is spent on services, higher-value goods and knowledge-intensive goods, thus reducing the material intensity of consumption. It has been suggested that the resulting declining growth in materials intensity may eventually lead to a decrease in a society's materials intensity (the 'inverted-U' hypothesis), which would have a significant positive impact on that society's environmental burden.
Several authors have contested the dematerialisation thesis. Labys and Waddell (1989) argue that society 'transmaterialises', through a process of materials substitution, rather than dematerialises. The intensity of use of materials in society does follow the typical S-shaped curve of growth, maturity and decline, but because the collection of data on the use of materials tends to lag behind in the introduction and growth stages, there is the suggestion of, but no real, dematerialisation.
De Bruyn and Opschoor (1997) propose that periods of dematerialisation are followed by periods of 'rematerialisation'. This pattern is explained by the evolutionary view of economic growth as a 'punctuated equilibrium'. Periods of stable economic growth are interrupted by clusters of innovations, according to Schumpeter's model of creative destruction. Whether or not there is dematerialisation depends on the relative importance of two rates over time: the rate of economic growth (measured as income) and the rate of efficiency gains in materials use. For dematerialisation to occur, it is at least necessary that the rate of efficiency gains is greater than the rate of economic growth. Since it is likely that during periods of stable economic growth any efficiency gains in productivity are used to increase production (Bunker 1996; Jackson and Clift 1998), an increase in materials intensity will be observed, i.e. rematerialisation. The resulting hypothesis is that dematerialisation will only be observed when radical structural or technological change occurs.
Others contest the dematerialisation thesis by pointing out that the materials intensity of industrialised countries tends to converge in a narrow range between 16 and 20 tons of material per capita per year, and that despite structural changes and growth of services in advanced economies, the intensity of flow of materials in economies is still growing in absolute terms (Vellinga et al. 1998).
It is not only the dematerialisation thesis itself that has been criticised; so has the proposition that dematerialisation would have environmental benefits. For example, if all material eventually dissipates into the environment, then a reduction in materials use in itself need not be beneficial if it is not considered how (in what form, what concentration) that material dissipates into the environment. It might be the case that a more intense use of a material allows for better containment, and reduction of dissipation rates, of that material into the environment (Vellinga et al. 1998), e.g. in the case of lead batteries for electric vehicles (Socolow and Thomas 1997).
Bunker (1996) points out that one of the consequences of declining intensity of materials use may be a deteriorating trade position for regional economies that depend on the extraction of raw materials and/or the export of minerals. In order to compensate for the loss of trade, such economies could intensify their production and expand on a low-cost basis into the higher added-value refining and processing steps, which in turn could result in a net relocation of polluting industries (cf. Larson et al. 1986).
Cleveland and Ruth (1998) conclude from extensive literature research into empirical results of dematerialisation studies that:

1. Knowledge of the extent of, and mechanisms behind, patterns of materials use is limited to individual materials or specific industries, mostly related to metals.
2. Although it may be the case that weight-based materials intensity is declining, it is unclear what the economic significance of that trend is, because of lack of measurement of aggregate material use;
3. Even less is known about the net environmental effects of changing materials use.

Conclusion

Industrial ecology is presented as a strong metaphor that may advance positive radical change in industrial resource efficiency and, consequently, in significant reduction of environmental pollution. Most of the research into industrial ecology focuses on describing materials flows and transformations and developing tools for controlling them. However, studies into the manageability of materials flows indicate, on the one hand, that currently market and regulatory failures exist which inhibit the implementation of the principles of industrial ecology and, on the other hand, that decisions of actors, such as firms and consumers, that shape the flow and transformation of materials – at least in the societal context – are only partly informed by prices, information and laws. These are major challenges for industrial ecology, not only in research but also in the practical implications for eco-industrial parks and dematerialisation.

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